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Towards sustainable TiO_2 production: An investigation of environmental impacts of ilmenite and rutile processing routes in Australia

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ABSTRACT

This paper presents life-cycle environmental impacts and health hazards of the ilmenite and rutile processing routes which are very little explored despite a significant quantity of production worldwide. The study is carried out through a life-cycle environmental-impact assessment of the ilmenite and rutile mining production processes in Australia, using the International Reference Life Cycle Data System (ILCD) method under 14 significant impact categories and the Cumulative Energy Demand (CED) method for 10 significant impact categories. The dataset is collected from EcoInvent and the Australian Life cycle assessment database considering Australia as the geographic region. The major impact categories are climate change, human health (cancer), human health (non-cancer), ecotoxicity, and eutrophication. The analysis results show that the highest impact is caused in climate change, at 0.295 kg CO_2 eq, which is due to the large amount of electricity consumption in the ilmenite extraction process. Then, human toxicity-non cancer effects (4.42E-09 CTUh) and particulate matter (0.000155 kg PM 2.5 eq) are also noteworthy. Water resources depletion is affected due to the chemical emissions from ilmenite ore, which are found to be 0.00163 m^3 water eq. Rutile production impacts greatly on climate change at 1.535 kg CO_2 eq owing to large-scale electricity consumption. Electricity consumption for rutile also affects human toxicity-non cancer (2.3E-8 CTUh), particulate matter (0.00081 kg PM2.5 eq), and terrestrial eutrophication (0.024 molc N eq). Water-resources depletion from rutile is due to the ore, which are found to be 0.0085 m^3 water eq. The comparative assessment between ilmenite and rutile implies that rutile has more impact on the environment than ilmenite due to the electricity consumption and fossil fuel consumption. This result is validated through further analysis using the Cumulative Energy Demand method. A sensitivity analysis is also carried out to elucidate that the electricity grid mix from country-to-country contributes to sustainability by reducing the environmental impacts significantly.

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1. Introduction

Ilmenite and rutile are the most commonly found and abundant form of titanium oxide. Ilmenite is weakly magnetic mineral sand, grey-black in color, solid in form, and exists in a triangle crystal structure. On the other hand, rutile is reddish-brown in color and exists in a tetragonal crystal structure. These heavy mineral sands are excavated and dredged, mostly to commercially produce ilmenite, rutile or other titanium-oxide ores. Originally, ilmenite and rutile are titanium oxides which may contain a variable amount of magnesium or manganese which is often dispersed from its original content (Abzalov, 2016). Ilmenite and rutile, being titanium-oxide minerals are used to produce high-performance metal parts such as artificial human-body parts, aircraft engine parts, sporting equipment, synthetic rutile, pigments etc. These pigments are used for whiten, in papers, paints, toothpaste, adhesive, plastic and foods and in nanotechnologies. From ilmenite ores, through the Becher process, synthetic rutile is produced, which is slightly yellowish and almost transparent in color (Pellegrino and Lodhia, 2012; Ranängen and Lindman, 2017; Raugei and Ulgiati, 2009).

Australia has one of the largest resources of ilmenite and rutile forms of titanium oxide and it is quite expected that Australia is facing the environmental impacts and health effects caused by the

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titanium-ore extraction process (Haque et al., 2014; Jones, 2009; Reichl et al., 2016). The effect of this processing route on human health and ecosystems needs to be identified and minimized to ensure a sustainable, environment-friendly extraction process in the long run.

The major environmental issues of concern from titanium oxide mining are pollution of ground-water resources, mineral transport with heavy vehicles, dredging operations in fragile coastal areas and deforestation. Many motives are associated with this question as to why the environmental impacts caused by mineral sand industries require urgent attention. The first issue is the proper rehabilitation of the abandoned mineral-sand deposits after the decommissioning or depletion of the mineral ore bodies because there is a possibility of leaching to ground-water resources from the abandoned mineral deposits. Moreover, elevated radiation hazards are associated with the mineral-sand loading and storage facilities which require advanced control systems. Secondly, there have been significant changes over the past 40 years in the mode of mining-industry operations, which further leads to the massive scale of the mining activities increasing the chance of abandoning the mineral sand deposits (Haque et al., 2014; Northey et al., 2016; Onn and Woodley, 2014). Thirdly, the reagents added during the secondary processing of mineral-sand deposits which may include chlorides for titanium-oxide processing and increases the radionuclide emission from the abandoned mineral sites to local ground-water systems, as mineral-sand extraction involves the extraction of soil up to 30 m depth or more, where the topsoil is removed prior to mining and then filled by the tailings from mining (Jones, 2009; Moran et al., 2014; Norgate and Haque, 2010; Sonter et al., 2014). As a result, mineral-sand mining leads to loss of trees and plants. All these issues had influenced some previous researchers to investigate the environmental impact assessment caused by the mineral industries with some suggestions for improvement (Durucan et al., 2006; Durucan and Korre, 2003, 1998; Farjana et al., 2018a, b; Frischknecht et al., 2000; Swensen, 1996).

Australia has a great resource for mineral-sand industry, the highest in the entire world, but as compared to the total deposit only a small fraction is currently being extracted. By ensuring an eco-friendly sustainable extraction process, Australia could potentially increase its current production of mineral sands like ilmenite and rutile. To facilitate that process, effective measures should be taken to make the mining extraction processes sustainable (Awuah-Offei and Adekpedjou, 2011; Law and Lane, 1991; Mudd, 2009; Navarro and Zhao, 2014; Norgate et al., 2007). Although the mining processes are impactful to the environment in different categories of global warming, greenhouse-gas-emissions, human health and ecotoxicity, such a critical issue has not been reported anywhere in the open literature that provides a comprehensive analysis of the environmental impacts caused by ilmenite and rutile mining technologies in Australia. This paper provides the knowledge gap with an effort to promote a sustainable extraction process of ilmenite and rutile in Australia. The paper starts with a brief introduction followed by a detailed overview of the ilmenite and rutile extraction processes and their mining technologies in Section 2. Section 3 introduces the global producers of the ilmenite and rutile forms of titanium oxide. Section 4 outlines the life-cycle inventory input and output datasets of both the ilmenite and rutile mining methods and detailed analysis results of the ilmenite-rutile production process. This section also discusses the life-cycle analysis results under the environmental-impact categories outlined. Furthermore, it also explains the environmental and human-health effects, government concerns and public awareness about titanium-oxide mining methods. Section 5 summarizes the whole paper in terms of scope and results, thus recommends the environmental-effect reduction methods for selected titanium-ore extraction processes.

2. Ilmenite-rutile mining and processing

Hard-rock mining methods are used for the recovery of mineral-sand products in some countries. Whereas in Australia, Iluka Resources entail dry mining, which involves the typical extraction of heavy mineral ores from entirely shallow, free-flowing, and hollow deposits. Dry mining requires transportation like trucks, loaders, excavators, or scrapers to recover ore from the mining plant. This transportation unit then delivers the ore to the wet concentration plant. For large ore bodies with low clay content, the wet method of mining is preferred. To reduce the cost in the wet method, dredging with bucket wheels and suction is done. On the other hand, dry methods involve earth-moving equipment to excavate and transport the mineral sand to a separate feed-preparation section. Pumpers or conveyors differentiate among various dry-mining processes. Another exception involves hydraulic mining using high-pressure water. Dredging is done depending on the variability of the ground condition and the amount of available water. After the rehabilitation studies, the land is cleared and preparation starts for mining. Topsoil and subsoil is removed, stripped, and stockpiled. Transportation like scrapers or trucks is utilized to collect and transport the ore from the mining plant. Then the ore is screened to make it free from oversized materials, which may include rocks or debris. These oversized items are then returned to the pit to be transferred to the concentrator plant via conveyor. The wet concentration process produces a higher grade heavy mineral concentrate. Spiral separators are then used to wash the ore through gravity separation. This process consumes a huge amount of water which is then recycled back to the clean-water-dam. The concentration process produces a mixture of valuable and non-valuable heavy-sand minerals. From this mixture, ilmenite, rutile, zircon, and monazite are then separated through dry processing. Ilmenite is a titanium-oxide mineral which is upgraded to 85 to 95 percent titanium oxide which in turn comes as rutile. Synthetic rutile production consists of two stages including pyro-metallurgical processing, while ilmenite is heated in a large rotary kiln. It produces iron oxide impurities within the crystal lattice. In the next stage, irons is removed by oxidation and leaching in hydrometallurgical processing (Indian Bureau of Mines, 2016; Jones, 2009; Mineral Deposits Limited, 2011; Nuss and Eckelman, 2014; U.S. Geological Survey, 2012). Fig. 1 illustrates the flow diagram for ilmenite-rutile extraction technologies.

3. Production and resources of ilmenite and rutile

Ilmenite and rutile are the most abundant sources of titanium-oxide in the world. A United States Geological Survey (USGS) report states that ilmenite accounts for 92% of the world's consumption of titanium oxide. China, with 20 million tonnes, has the world's most abundant source of ilmenite while Australia stands in the first position for rutile with a 29 million tonne reserve (USGS, 2017). Fig. 2 shows data in thousands of metric tonnes of titanium-oxide. It also illustrates the global producers of ilmenite-rutile throughout the world based on their production and reserve. In terms of production, Norway and South Africa dominate over China and Australia. On the other hand, Australia have the largest resource and production system of rutile while South Africa comes in the second position for reserve (Agency et al., 2014; Mudd, 2009).

Table 1 summarizes the current mineral-sand mining operations in Australia. There are 15 operating mines which produce ilmenite-rutile in Australia. In the early years, Australia produced 1 million tonnes of ilmenite of which nearly half were converted into synthetic rutile through the Becher process. Now a days around 50%

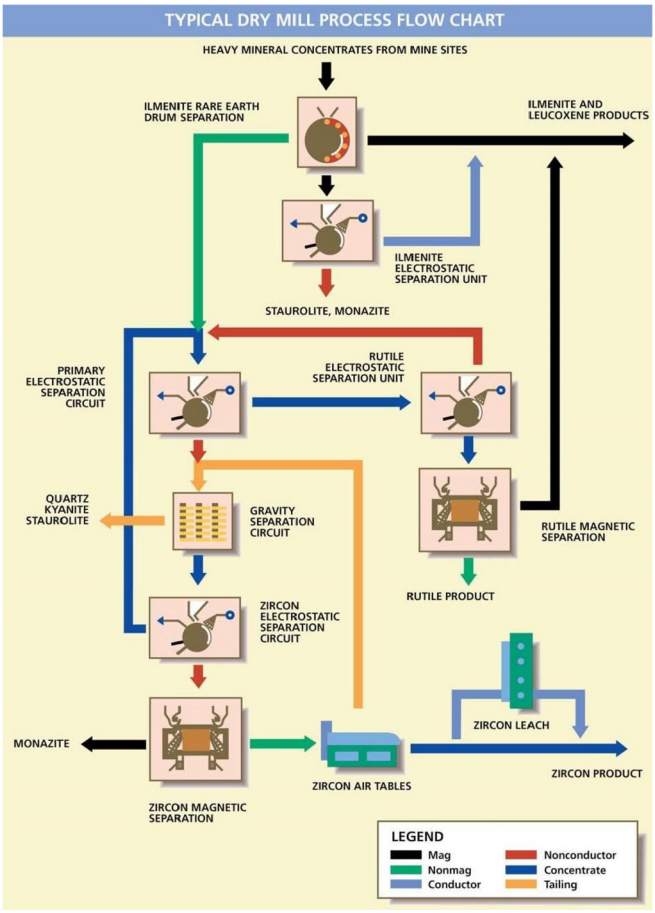


Fig. 1. Ilmenite-rutile mining and processing technologies (Jones, 2009).

of ilmenite is exported without being converted into rutile. Australia supplies nearly 25% of the world's rutile. (Mudd, 2000, 2009).

4. Materials and methods

Life-cycle assessment analyzes and calculates the environmental effects and impacts caused by the process or product while manufacturing throughout its entire life-cycle from cradle to grave, cradle to gate, gate to grave or whatever. LCA works through identification and quantification of input materials, energy and resources and output products and emissions to the environment like air, water or soil. The LCA methodology in this study is based on the International Organization for Standards (ISO 14040) which follows four mandatory stages which are required to be completed: goal and scope definition, life-cycle inventory, life-cycle impact assessment, and interpretation and recommendation of the inventory and results (Durucan et al., 2006; Durucan and Korre, 2003, 1998; Onn and Woodley, 2014). SimaPro software version 8.5 is used for analysis and comparison.

4.1. Goal and scope definition

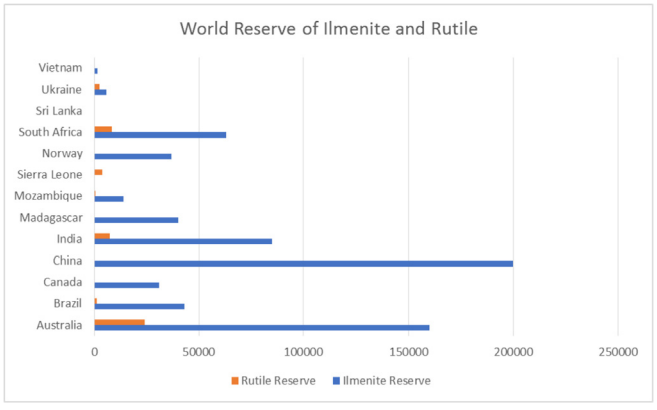
The goal of this research work is to analyse the life-cycle environmental impact of ilmenite and rutile in Australia. The scope of this research work is the several impact categories assessed by the ILCD method and 10 impact categories assessed by CED method. This paper also addresses the dependency of the environmental impacts of the mineral sand extraction processes on the electricity grid mix The life-cycle impact assessment is done using SimaPro software version 8.4. The datasets are collected from the Australian System Process dataset (AusLCI) for different mines in Australia. The analysis methods are chosen as the ILCD method and the CED method. The processes are cradle-to-gate life-cycle impact assessment. The functional unit is 1 kg of mineral sands. Figs. 3 and 4 illustrate the material flow sheet for ilmenite and rutile processing (Lesage et al., 2008).

4.2. Life-cycle inventory

These datasets are system process datasets where the key components or the emissions are divided under the categories of energy generation related to ilmenite/rutile production, diesel, hard coal, natural gas, heavy fuel, electricity. Fig. 5 graphically represents the system boundary diagram used in this study. Table 2 shows the comparative input datasets of the ilmenite and rutile extraction processes. Table 3 provides the outputs of the ilmenite and rutile extraction process where the functional unit for both processes is 1 kg of mineral sand. It also shows the radioactive emissions associated with mining activities such as uranium ions, thorium ions and radium ions (Navarro and Zhao, 2014; Norgate et al., 2007).

4.3. Life-cycle impact analysis

In this section, the subsections describe the life-cycle impact-assessment results under various impact-analysis criteria based on the ILCD and CED methods. The ILCD method is the International



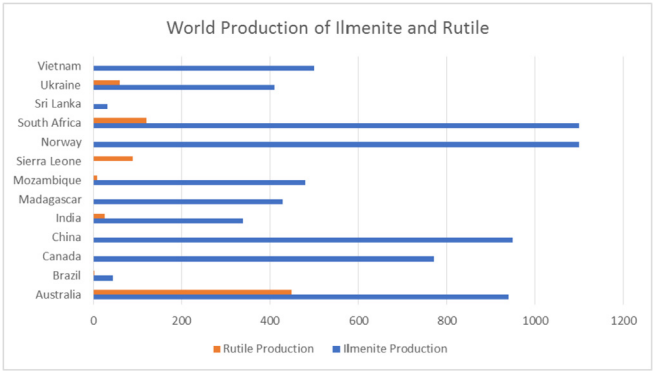


Fig. 2. (a)World production and reserve of ilmenite-rutile- reserves. (b). World production and reserve of ilmenite-rutile- -production.

Table 1
Major ilmenite-rutile mines in Australia.

	Name of the mine	Company Name
Western Australia	Eneabba area	Iluka Resources Ltd
	Windimurra (Atlantic)	Maximus Resources Limited
	Cooljarloo (TRONOX)	Tiwest JV
	Dardanup (Doral)	Iwatani International Corporation
	Port Gregory	
	Tutunup South	Iluka Resources Ltd
	Wonnerup North	
New South Wales	Snapper	BeMax Resources NL
	Ginkgo	BeMax Resources NL
Victoria	Kulwin, Woornack, Rownack, Pirro	Iluka Resources Ltd
	Murray Basin	Iluka Resources Ltd
Queensland	North Stradbroke Island	Consolidated Rutile Ltd
Tasmania	Scotia	
	Eucla Basin (Jacinth Ambrosia, Atacama, Typhoon, Sonoran, Tripitaka)	Iluka Resources Ltd
	Mindarie	Australian Zircon NL

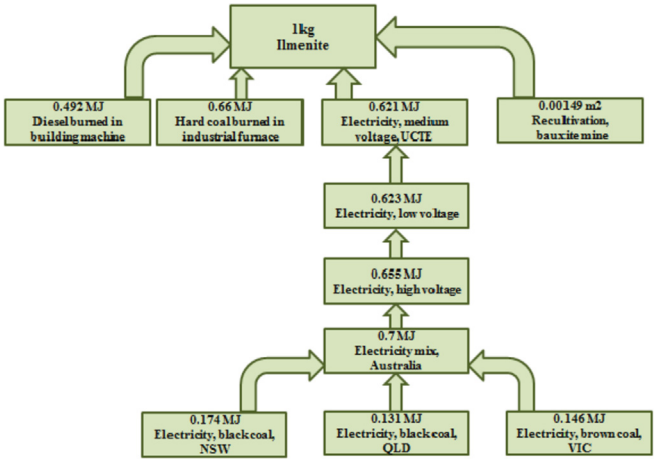

1kg Ilmenite
0.492 MJ Diesel burned in building machine
0.66 MJ Hard coal burned in industrial furnace
0.621 MJ Electricity, medium voltage, UCTE
0.00149 m2 Recultivation, bauxite mine
0.623 MJ Electricity, low voltage
0.655 MJ Electricity, high voltage
0.7 MJ Electricity mix, Australia
0.174 MJ Electricity, black coal, NSW
0.131 MJ Electricity, black coal, QLD
0.146 MJ Electricity, brown coal, VIC

Fig. 3. Materials flow sheet for ilmenite processing.

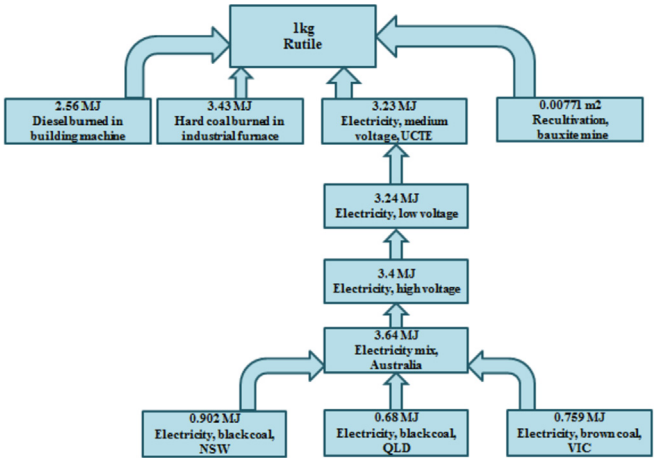

1kg Rutile
2.56 MJ Diesel burned in building machine
3.43 MJ Hard coal burned in industrial furnace
3.23 MJ Electricity, medium voltage, UCTE
0.00771 m2 Recultivation, bauxite mine
3.24 MJ Electricity, low voltage
3.4 MJ Electricity, high voltage
3.64 MJ Electricity mix, Australia
0.902 MJ Electricity, black coal, NSW
0.68 MJ Electricity, black coal, QLD
0.759 MJ Electricity, brown coal, VIC

Fig. 4. Materials flow sheet for rutile processing.

Reference Life Cycle Data System (ILCD) method, which is a standard method based on ISO 14040 and developed by the European Commission, Institute for Environment and Sustainability. This LCIA method considers 14 significant midpoint impact categories. For life-cycle analysis in the Australian geographic context, the Australian Indicator method seems to suit best, but it has a major limitation. This method only considers weighting for climate-change category but it is a key feature for LCA analysis. Moreover, the ILCD method is a more robust and complete method and is a combination of CML, ReCiPe, IPCC, and EcoTox methods. In the second step, cumulative energy demand method is used for assessment of the energy (renewable and non-renewable) consumptions in the mineral-sands processing routes. In the third step sensitivity analysis is carried out to illustrate the electricity-grid-mix-dependency of mineral sand extraction processes in Australia. Fig. 6 shows the life-cycle impact-assessment methodology followed in this study, based on the ILCD and CED method (Curran, 2012; Farjana et al., 2018b; Parvez Mahmud et al., 2018; PE International, 2014; PE International AG, 2012).

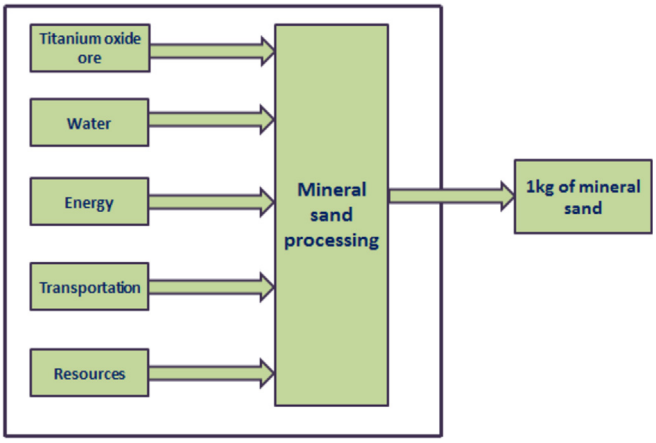


Fig. 5. System boundary for mineral - sand processing followed in this research.

4.3.1. Comparative impact assessment results from ILCD method

The detailed comparative impact-analysis results from the ilmenite and rutile - extraction processes are provided in Table 4. In the climate-change category, climate-change effects are greatest, at 1.53 kg CO_2 eq from rutile and 0.295 kg CO_2 eq from ilmenite. Ilmenite processing produces 0.000155 kg of PM2.5 eq particulate matter while rutile processing has impacts like 0.00081 khPM2.5 eq. In terms of eutrophication, the impact is 0.00469 molc N eq from ilmenite and from rutile it is 0.024 molc N eq. For human toxicity, the effect is measured on CTUh and rutile (1.25E-9 CTUh) has effects larger than ilmenite (2.41E-10 CTUh).

Figs. 7 and 8 show the impact assessment results using the ILCD method. Fig. 7 graphically represents the normalized results from

Table 2
Input inventory datasets for ilmenite and rutile manufacturing processes.

Input	From	Ilmenite	Rutile	Unit
TiO_2	Nature	0.56875	1	kg
Transformation, from forest	Nature	0.000594	0.00308	m^2
Transformation, from pasture and meadow	Nature	0.000891	0.00462	m^2
Transformation, to mineral extraction site	Nature	0.001485	0.00771	m^2
Occupation, mineral extraction site	Nature	0.01485	0.0771	m^2
Water, well, in ground	Nature	0.00968	0.0502	m^3
Diesel, burned in building machine	Materials/fuels	0.286	1.4857	MJ
Hard coal, burned in industrial furnace 1−10MW/RER U	Materials/fuels	0.66	3.4285	MJ
Natural gas, burned in industrial furnace >100kW/RER U	Materials/fuels	0.198	1.0285	MJ
Heavy fuel oil, burned in industrial furnace 1 MW, non-modulating	Materials/fuels	0.066	0.3428	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	Materials/fuels	0.16775	0.87143	kWh
Mine	Materials/fuels	2.20E-10	1.14E-9	p
Recultivation	Materials/fuels	0.001485	0.0077143	m^2

Table 3
Output inventory dataset of ilmenite-rutile manufacturing processes.

Output	Emissions to	Ilmenite	Rutile	Unit
54% titanium dioxide, at plant	Product	1	1	kg
Particulates, > 10 μm	Air	0.000079	0.00041	kg
Particulates, > 2.5 μm, and <10 μm	Air	0.000041	0.00021	kg
Particulates, < 2.5 um	Air	0.000016	0.000085	kg
Uranium-238	Air	0.0000091	0.000047	kBq
Thorium-232	Air	0.000019	0.0001	kBq
Radium-226	Air	0.0000315	0.00016	kBq
Heat, waste	Air	0.603	3.13714	MJ
Suspended solids, unspecified	Water	0.000025	0.00013	kg
Iron, ion	Water	0.0000012	6.57E-6	kg

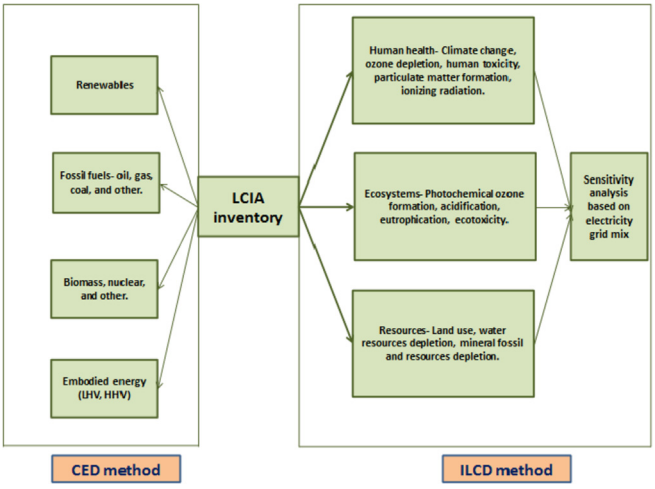

Renewables
Fossil fuels- oil, gas, coal, and other.
Biomass, nuclear, and other.
Embodied energy (LHV, HHV)
LCIA inventory
Human health- Climate change, ozone depletion, human toxicity, particulate matter formation, ionizing radiation.
Ecosystems- Photochemical ozone formation, acidification, eutrophication, ecotoxicity.
Resources- Land use, water resources depletion, mineral fossil and resources depletion.
Sensitivity analysis based on electricity grid mix
CED method
ILCD method

Fig. 6. LCA methodology used in this research.

the ILCD method. Fig. 8 illustrates the single-score results of ilmenite and rutile processing routes, which reveals the weighted scores of all impact categories in a single unit to assess the environmental effects. Among the sub-systems of ilmenite mining activities, most of the emissions are due to electricity consumption in mining activities. The second-largest contributor to global-warming emission is hard coal. Similar results are obtained for rutile mining processes. From the comparison between ilmenite and rutile, rutile effects are significantly larger than ilmenite-extraction operations. The major impact categories from the life-cycle impact assessment of ilmenite-rutile mineral extraction activities are the climate change, particulate matter, terrestrial eutrophication, human toxicity-non cancer, and water resources depletion. Under these categories, electricity generation contributes the most while the heat generation from diesel contributes the second most. But the scenario is quite different for the ozone-depletion potential of terrestrial ecosystems, while heavy fuel oil contributes the most. Eutrophication is the potential of adding excessive nutrients to water resources or ground-water resources from the mining or manufacturing process. For freshwater eutrophication, the electricity generation of the ilmenite mining process has a severe impact rather than the rutile manufacturing process, where in total ilmenite is higher than the rutile mining process. Ecotoxicity is the chemical or biological effects caused by the chemical reactions of the manufacturing or production processes on the ecosystems. The categories considered here are terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and marine aquatic ecotoxicity. In all these categories, the result is consistent: the highest impact is caused by the electricity consumed in the mining and extraction process for both ilmenite and rutile. The second-largest contributor is the heavy-fuel-oil based mining process. Overall, rutile has larger environmental impacts than ilmenite. The human Toxicity Potential (HTP) is a quantitative toxic equivalency potential (TEP) that illustrates the harmful effects of a unit of chemical released. The categories considered here are human toxicity, carcinogenic and non-carcinogenic, and the overall human toxicity obtained from the ILCD method. The analysis results are similar to those presented before under various categories, and the results indicate that the electricity consumption for the mineral-sands mining process is the largest contributor for both ilmenite and rutile, with rutile effects larger than for ilmenite. The second largest contributor is the diesel-fuel-based mining process which is consistent with some of findings reported previously.

4.3.2. Comparative impact assessment results from CED method

Table 5 represents the LCIA results from the Cumulative Energy Demand method (CED) which assessed the breakdown of the fuel

Table 4
Comparative life-cycle impact-assessment results based on ILCD method.

Impact category	Unit	Ilmenite,54% titanium dioxide	Rutile,95% titanium dioxide, at plant
Climate change	kg CO_2 eq	0.2954	1.535
Ozone depletion	kg CFC-11 eq	6.28E-09	3.26E-08
Human toxicity, non-cancer effects	CTUh	4.42E-09	2.30E-08
Human toxicity, cancer effects	CTUh	2.41E-10	1.25E-09
Particulate matter	kg PM2.5 eq	0.000155	0.00081
Ionizing radiation HH	kBq U235 eq	1.50E-05	7.79E-05
Ionizing radiation E (interim)	CTUe	9.37E-13	4.87E-12
Photochemical ozone formation	kg NMVOC eq	0.00123	0.00644
Acidification	molc H+ eq	0.00138	0.0072
Terrestrial eutrophication	molc N eq	0.00469	0.0243
Freshwater eutrophication	kg P eq	1.70E-07	8.85E-07
Marine eutrophication	kg N eq	0.000437	0.0022
Freshwater ecotoxicity	CTUe	0.0175	0.091
Land use	kg C deficit	0.332	1.728
Water resource depletion	m^3 water eq	0.00163	0.0085
Mineral, fossil & renewable resource depletion	kg Sb eq	2.05E-16	1.06E-15

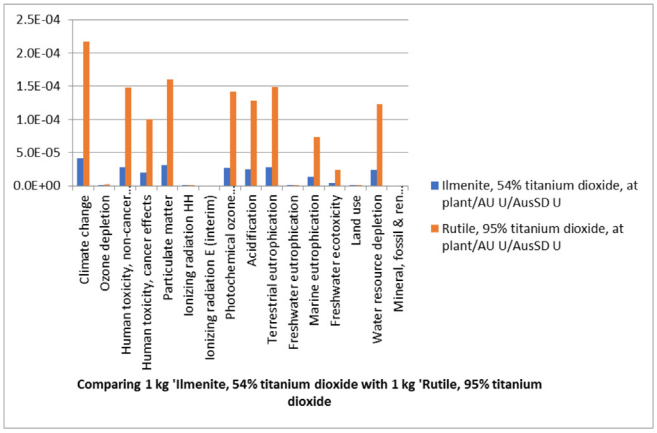


Fig. 7. Comparative life-cycle impact-assessment results based on ILCD method - normalized results.

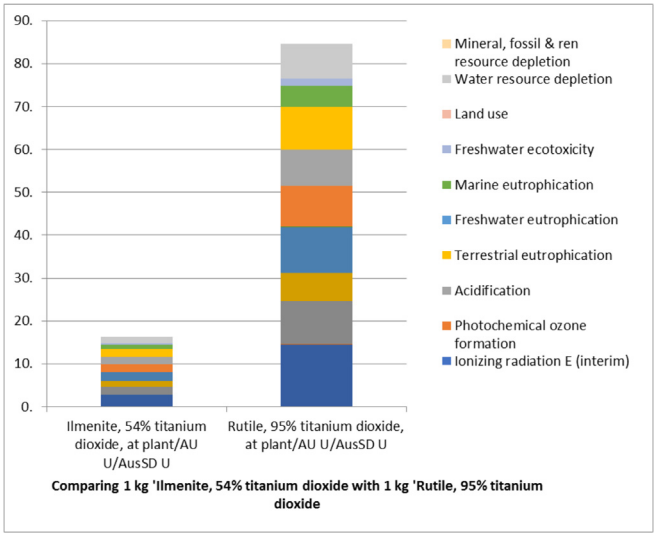


Fig. 8. Comparative life-cycle impact-assessment results based on ILCD method - single score results.

used throughout the mineral-sands processing of ilmenite and rutile from the titanium-oxide ores. Fig. 9 illustrates the major energy intensive process. The fuel inputs considered here across the mineral-sand processing systems are fossil fuels, renewables, nuclear, biomass, embodied energy (lower heating values), embodied energy (higher heating values) and other energy sources. Fig. 9 illustrates that the highest environmental threat from mineral processing is due to the usage of fossil fuels, mostly coal. The reason behind this result is the huge amount of electricity consumption in mineral processing. In Australia, the major source of electricity generation is coal, which is found in abundance in a number of major coal mines located in Australia. The second-largest energy is consumed in other forms of fossil fuels, such as oil and gas. Diesel is consumed in diesel-electric generating unit and also burned in building machines. A comparison between ilmenite and rutile processing is presented in Fig. 9 which shows that rutile is much more energy-intensive mineral sand than ilmenite, due to the fact that the lower ore grade consumes a greater amount of energy, extracted from the core of the earth.

4.3.3. Sensitivity analysis of ilmenite and rutile extraction routes based on electricity grid mix

Table 6, Table 7, and Table 8 provide the sensitivity-analysis results based on the electricity grid mix of different regions. The goal of this analysis is to identify and discuss the effects of electricity on mineral-sand processing, as electricity generation and consumption is the greatest contributor to these effects. 7 different case scenarios are considered including the base case scenario. The electricity grid mixes and their inventories are collected from EcoInvent database which is further considered for sensitivity analysis.

In the base case of Australia, the electricity grid mix is considered for UCTE (Union for the Co-ordination of Transmission of Electricity). The other cases are electricity grid mix for CENTRAL (Central European Power Association), CH (Switzerland), DE (Germany), NL (Netherlands), NORDEL (Nordic Countries Power Association), and RER (Europe). Different regional areas utilize different energy mixes for their electricity generation. The energy mixes vary in terms of renewable energy utilization for electricity generation, source of fossil fuels utilized in electricity generation, small-scale and large-scale hydroelectric power, etc. Each set of electricity grid mix have specific properties which significantly affects sustainability. From the analysis results presented below in Table 6 for ilmenite, the annual electricity production in the UCTE network is 2577860 GWh with Germany, France, Spain, and Italy. The annual production in the NORDEL network is 394639 GWh with Sweden and Norway. The annual production in the CENTREL network is 270588 GWh with Poland and the Czech Republic as the main

Table 5
Comparative life-cycle impact-assessment results based on CED method.

Impact category	Unit	Ilmenite, 54% titanium dioxide	Rutile, 95% titanium dioxide
Renewables	MJ LHV	0.0789	0.41
Fossil fuels - oil	MJ LHV	0.6828	3.547
Fossil fuels - gas	MJ LHV	0.5621	2.92
Fossil fuels - coal	MJ LHV	2.1113	10.968
Fossil fuels - other	MJ LHV	0	0
Biomass	MJ LHV	0.0006	0.00345
Nuclear	MJ LHV	1.27E-05	6.60E-05
Other/Unknown	MJ LHV	0	0
Embodied energy LHV	MJ LHV	3.435	17.849
Embodied energy HHV	MJ HHV	3.52	18.286

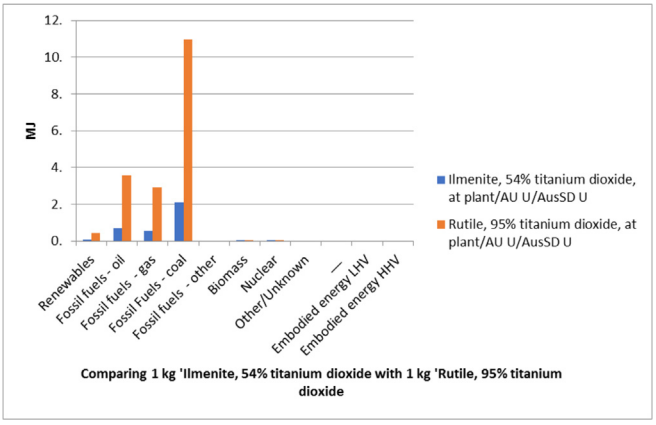


Fig. 9. Comparative life-cycle impact-assessment results based on CED method - weighted results.

producers (Frischknecht et al., 2015; Itten et al., 2014). The annual production in the RER network corresponds to the production in the ENTSO-E network excluding the Baltic States. There are some electricity losses due to transmission, which is dependent on the population density in the different countries and on the infrastructure of technology. The statistics of global electricity production show that, in Australia, around 92.2% of the total electricity production is based on fossil-fuels and around 5% of production is from hydropower. In Switzerland, fossil fuel based electricity generation is only 2.45%, while most of the electricity generation is from hydropower (around 60%). In Germany, fossil-fuel only generates 60% of the total electricity production, while the rest comes from nuclear power (around 23%) and hydropower (around 5%). The Netherlands produce electricity based on fossil fuels (around 85%). After briefly analyzing the electricity mixes from different technologies and fuel sources for different countries, it is evident that Australia is one of the leading countries utilizing fossil fuels for

Table 6
Electricity grid mix details.

Electricity grid mix	Annual electricity production	Producer
Australia- UCTE(Union for the Co-ordination of Transmission of Electricity)	2577860 GWh	Germany, France, Spain, and Italy
CENTRAL (Central European Power Association)	270588 GWh	Poland and the Czech Republic
NORDEL (Nordic Countries Power Association)	394639 GWh	Sweden and Norway

Table 7
Sensitivity-analysis results for ilmenite - based on 7 different grid mix scenarios.

Ilmenite		Electricity, at UCTE	Electricity, at CENTRAL	Electricity, at CH	Electricity, at DE	Electricity, at NL	Electricity, at NORDEL	Electricity, at RER
Impact category	Unit	Total	Total	Total	Total	Total	Total	Total
Climate change	kg CO_2 eq	2.95E-01	2.74E-01	1.30E-01	2.35E-01	2.46E-01	**2.96E-01**	2.08E-01
Ozone depletion	kg CFC-11 eq	6.28E-09	7.25E-09	8.36E-09	**9.21E-09**	7.02E-09	6.28E-09	7.85E-09
Human toxicity, non-cancer effects	CTUh	4.42E-09	1.07E-08	3.19E-09	5.90E-09	4.78E-09	4.42E-09	**6.02E-09**
Human toxicity, cancer effects	CTUh	2.41E-10	**1.64E-09**	1.87E-10	4.24E-10	2.02E-10	2.41E-10	4.88E-10
Particulate matter	kg PM2.5 eq	1.56E-04	**1.96E-04**	1.41E-04	1.56E-04	1.70E-04	1.56E-04	1.77E-04
Ionizing radiation HH	kBq U235 eq	1.50E-05	1.27E-02	**3.23E-02**	9.29E-03	2.53E-03	1.50E-05	2.16E-02
Ionizing radiation E (interim)	CTUe	9.37E-13	1.14E-07	**2.54E-07**	8.48E-08	2.27E-08	9.37E-13	1.95E-07
Photochemical ozone formation	kg NMVOC eq	**0.00123**	1.10E-03	8.18E-04	9.13E-04	9.72E-04	1.24E-03	9.70E-04
Acidification	molc H+ eq	**0.00138**	1.94E-03	1.09E-03	1.24E-03	0.00126	**0.00138**	1.49E-03
Terrestrial eutrophication	molc N eq	4.69E-03	3.95E-03	2.96E-03	3.32E-03	3.55E-03	4.69E-03	**0.00349**
Freshwater eutrophication	kg P eq	**1.70E-07**	4.74E-08	1.82E-08	4.62E-08	9.31E-08	**1.70E-07**	6.68E-08
Marine eutrophication	kg N eq	**0.000431**	3.61E-04	2.70E-04	0.0003	0.00032	**0.000431247**	0.000319
Freshwater ecotoxicity	CTUe	**0.0175**	4.10E-02	1.53E-02	1.90E-02	1.68E-02	**1.75E-02**	0.025083551
Land use	kg C deficit	**0.3327**	3.44E-01	3.36E-01	3.42E-01	0.3478	**0.3327**	3.42E-01
Water resource depletion	m^3 water eq	**0.0016**	2.44E-03	0.00168	0.0022	0.0019	**0.0016**	0.002076
Mineral, fossil & ren resource depletion	kg Sb eq	2.05E-16	3.11E-16	2.54E-16	**4.61E-15**	2.22E-15	2.05E-16	1.68E-15

Table 8
Sensitivity-analysis results for rutile-based on 7 different grid mix scenarios.

Rutile		Electricity, at UCTE	Electricity, at CENTRAL	Electricity, at CH	Electricity, at DE	Electricity, at NL	Electricity, at NORDEL	Electricity, at RER
Impact category	Unit	Total	Total	Total	Total	Total	Total	Total
Climate change	kg CO_2 eq	**1.54E+00**	1.42E+00	6.78E-01	1.22E+00	1.28E+00	**1.54E+00**	1.08E+00
Ozone depletion	kg CFC-11 eq	3.26E-08	3.76E-08	4.34E-08	**4.78E-08**	3.64E-08	3.26E-08	4.08E-08
Human toxicity, non-cancer effects	CTUh	2.30E-08	**5.56E-08**	1.66E-08	3.07E-08	2.48E-08	2.30E-08	3.12E-08
Human toxicity, cancer effects	CTUh	1.25E-09	**8.51E-09**	9.71E-10	2.20E-09	1.05E-09	1.25E-09	2.53E-09
Particulate matter	kg PM2.5 eq	8.10E-04	1.02E-03	7.32E-04	8.09E-04	8.81E-04	**0.00081**	9.21E-04
Ionizing radiation HH	kBq U235 eq	7.79E-05	6.59E-02	**1.68E-01**	4.83E-02	1.32E-02	7.79E-05	1.12E-01
Ionizing radiation E (interim)	CTUe	4.87E-12	5.94E-07	**1.32E-06**	4.41E-07	1.18E-07	4.87E-12	1.01E-06
Photochemical ozone formation	kg NMVOC eq	6.44E-03	5.70E-03	4.25E-03	4.74E-03	5.05E-03	**0.00644**	5.04E-03
Acidification	molc H+ eq	**0.0072**	1.01E-02	5.65E-03	6.42E-03	0.0065	**0.0072**	7.74E-03
Terrestrial eutrophication	molc N eq	2.44E-02	0.0205	0.0153	0.0172	1.85E-02	**0.0243**	1.82E-02
Freshwater eutrophication	kg P eq	**8.85E-07**	2.46E-07	9.46E-08	2.40E-07	4.84E-07	**8.85E-07**	3.47E-07
Marine eutrophication	kg N eq	**0.00224**	1.87E-03	1.40E-03	1.57E-03	1.68E-03	**0.00224**	1.66E-03
Freshwater ecotoxicity	CTUe	9.10E-02	2.13E-01	7.92E-02	9.86E-02	8.71E-02	0.091001	**0.130305**
Land use	kg C deficit	1.728695	1.79E+00	1.74E+00	1.77E+00	**1.806**	1.728	1.777
Water resource depletion	m^3 water eq	8.51E-03	**0.0126**	0.0087	0.011599	1.01E-02	0.0085	0.01
Mineral, fossil & renewable resource depletion	kg Sb eq	1.06E-15	1.62E-15	1.32E-15	**2.40E-14**	1.16E-14	1.06E-15	8.71E-15

electricity generation (Frischknecht et al., 2015; Itten et al., 2014).

The analysis results presented in Table 7, Table 8, and Fig. 10 clarify the fact that electricity grid mix based on UCTE is one of the greatest impactful grid mix scenario. Table 7 shows the sensitivity analysis results of ilmenite processing, based on 7 different grid mix scenario. The results shows that sensitivity varies depending on the grid mix scenario and impact category. NORDEL electricity mix is harmful for environment over the other grid mixes in the categories of climate change, acidification, eutrophication, ecotoxicity, and land use. Similar results come from UCTE network, which means for Australia, UCTE grid mix sensitivity results are almost similar like NORDEL. CENTRAL electricity mixes are harmful for human toxicity (cancer effects) and particulate matter. Switzerland electricity mix is impactful on ionizing radiation. In Europe (RER), it has significant impacts on human toxicity. Electricity mix of Germany is impactful for ozone depletion and mineral resources depletion. Among the seven electricity grid mix scenarios considered for ilmenite processing routes, the electricity grid mix used in Netherland is the most sustainable. This is due to lowest consumption of fossil fuels. The highest impact is caused by the

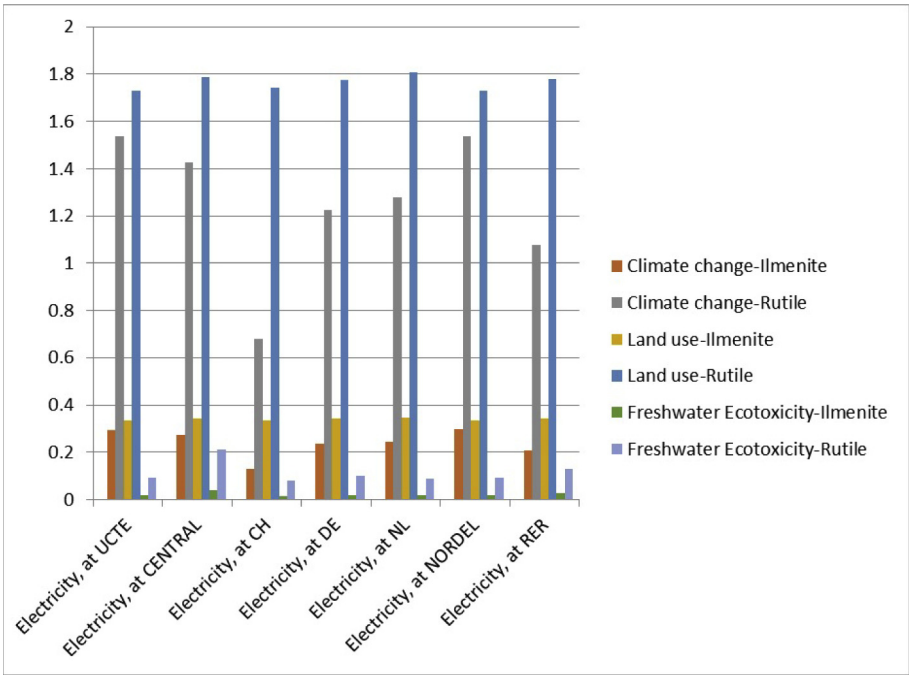


Fig. 10. Major impact category results based on 7 different electricity grid mixes.

electricity grid mix in the NORDEL network and UCTE network, due to more than 80% being fossil-fuel based. Among all the impact categories assessed by the ILCD method, the most sensitive categories due to electricity generations are climate change, land use, and freshwater ecotoxicity. (Frischknecht et al., 2015; Itten et al., 2014; Paraskevas et al., 2016; Santero and Hendry, 2016; Tost et al., 2018; Tuusjärvi et al., 2014; Vintró et al., 2014; Farjana et al., 2018a, b).

Table 8 shows the sensitivity analysis results of rutile processing, based on 7 different grid mix scenario. The results show that sensitivity varies depending on the grid mix scenario and impact category. NORDEL electricity mix is harmful for environment over the other grid mixes in the categories of climate change, acidification, eutrophication, ecotoxicity, and photochemical ozone formation. UCTE grid mix sensitivity results are almost similar like NORDEL one which is impactful for climate change, eutrophication, and acidification. CENTRAL electricity mixes are harmful for human toxicity (cancer effects and non-cancer effects) and water resources depletion. Switzerland electricity mix is impactful on ionizing radiation. In Europe (RER), it has significant impacts on freshwater ecotoxicity. Among the seven electricity grid mix scenarios considered for rutile processing routes, the electricity grid mix used in Germany is the most sustainable. Among the 14 major impact categories assessed by the ILCD method for rutile processing, the most sensitive categories due to electricity generations are climate change, land use, and freshwater ecotoxicity. As rutile processing is more energy-intensive due to ore grades, it consumes more electricity and has a greater effects on sustainability (Frischknecht et al., 2015; Itten et al., 2014; Paraskevas et al., 2016; Santero and Hendry, 2016; Tost et al., 2018; Tuusjärvi et al., 2014; Vintró et al., 2014; Farjana et al., 2018a; b).

Fig. 10 illustrates the comparison among the sensitivity analysis results of different categories (climate change, land use, freshwater ecotoxicity) for the seven different electricity grid mix scenario. Both ilmenite and rutile are considered and compared here. The analysis results indicate the level of uncertainty among the impact values. In terms of climate change, both ilmenite processing and rutile processing is more sustainable in Switzerland over other case scenarios. Land use is another affected category from these mineral processing routes, while NORDEL shows the highest level of sustainability. In case of freshwater ecotoxicity, UCTE network shows the higher level of sustainability. The reasons behind these varied analysis results are the consumption of fossil fuels used for the electricity generation. Because in ilmenite and rutile processing, minerals consumes huge amount of electricity to be produced, this has enormous effects on sustainability. Integration of the renewable energy resources to the mineral processing systems can contribute to make the mineral miner countries more sustainable (Farjana et al., 2018b, 2018a; Hisan et al., 2018)

5. Conclusion

In summary, this paper addresses the environmental impacts caused by the ilmenite and rutile extraction processes through detailed mid-point indicator based life-cycle assessment, material-flow analysis, and sensitivity analysis based on electricity grid mix of different global regions. The significance of this work is to access the sustainability issues of the mineral-sand industry in Australia, as Australia has one of the largest reserves and production of ilmenite and rutile. The life-cycle impact-analysis results of ilmenite and rutile processing routes and the corresponding sensitivity analysis based on electricity grid mix shows that a significant environmental impact is caused by the rutile mining process over the ilmenite mining process. The reason behind this is that ilmenite is produced from 54% titanium oxide with a higher ore grade where rutile is produced from 95% titanium oxide with lower ore grade. Extracting the low-grade rutile is more energy intensive than extracting the higher-grade ilmenite in addition to the fact that rutile is extracted from deep mines. The analysis results indicate that the major contributor for both the ilmenite and rutile mining process is electricity consumption, because a significant amount of electricity is consumed during the mining and milling processes of mineral sand industries. An exception is found for the rutile production processes in the eutrophication category, where diesel energy based process is the greatest contributor. The hard coal-based production phase is in the second position for global warming potential, acidification potential and eutrophication. Diesel-based production process is the second-largest contributor for ozone formation and human toxicity. For ecotoxicity, heavy fuel oil effects are significantly greater than the diesel-oil and hard-coal based production phases. Overall, the results found from this research show that a significant environmental hazard is generated from the mineral sand industries in Australia, which will continue to increase because of the depletion of higher-grade minerals, which will led to deeper mining of lower-grade mineral sands. Finally, the results presented and discussed in this paper elucidate some valuable insights of the impacts generated from the mineral-sand industries in Australia and will surely help to minimizing some of the impacts by taking appropriate measures.

Nomenclature

kg CO_2 eq	Carbon dioxide equivalent
kg CFC-11 eq	Ozone Depletion Potential OZDP kg CFC-11 eq
CTUh	Comparative Toxic Unit for human
kg PM2.5 eq	Human Health Particulate
kBq U235 eq	a decay of 1000 U 235 nuclei per second
CTUe	Comparative Toxic Unit for ecosystems
kg NMVOC eq	Non-methane volatile organic compounds (**NMVOCs**) equivalent units
molc H+ eq	Acidification units
molc N eq	Terrestrial eutrophication
kg P eq	Freshwater eutrophication **kg P eq**
kg N eq	Eutrophication potential for air emissions
kg C deficit	kilograms of carbon deficit
m3 water eq	Volume of water
kg Sb eq	Abiotic depletion equivalent

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